# PEDOGENIC CALCRETES IN THE OLD RED SANDSTONE FACIES (LATE SILURIAN—EARLY CARBONIFEROUS) OF THE ANGLO-WELSH AREA, SOUTHERN BRITAIN

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## INTRODUCTION

The records of simple forms of life and of an oxygenated atmosphere extend so far back in geological time that sedimentologists have been forced to accept that all but the very oldest continental red-beds may be expected to include materials either modified or created by pedological processes. Such materials, however, arranged vertically in horizons to form paleosols, have so far been generally recognized in only the most obvious cases. This is partly because many of the criteria for a pedogenic origin are seemingly destroyed or modified beyond recognition during burial and lithification, but also because of the relative neglect by neopedologists, from whom comparative data must in the first instance be sought, of the evolution of soil environments on a geological time-scale. Thus paleosols have so far been claimed from only two of the three great continental red-bed successions present in the British Isles. None are reported from within the thick and extensive Torridonian (late Precambrian) rocks of north-west Scotland, although this formation rests locally on a paleosol (Williams, 1968). In the Old Red Sandstone (late Silurian-early Carboniferous) facies, however, paleosols have proved to be widespread and quite varied, although the soil materials so far recognized are restricted to the most resistant to diagenesis. Calcretes and some silcretes are known from the rocks in Scotland and the Scottish Border country (Burgess, 1961; Leeder, 1976; Parnell, 1983a, 1983b). Both the Lower and the Upper Old Red Sandstone in the Anglo-Welsh area abound in calcretes (Pick, 1964; Allen, 1965, 1974a), some of which are associated with a little barytes and others with concentrations of iron and manganese minerals. Calcretes are also present in the Old Red Sandstone facies to the south

in North Devon (Tunbridge, 1981a). It is only in the exceptionally thick and rapidly accumulated Upper Old Red Sandstone (mid to late Devonian) of southern Ireland that calcretes have proved to be infrequent and poorly developed (e.g. MacCarthy *et al.*, 1978; Gardiner and Horne, 1981). The Middle Devonian fluvial rocks of the Belgian Ardennes are also known to include carbonate-bearing paleosols (Molenaar, 1984). Well-developed calcretes are locally important in the New Red Sandstone (Permo-Triassic), the youngest major red-bed succession in the British Isles (Steel, 1974). Fossil calcretes and carbonate-bearing soils also have a wide distribution outside the British Isles, as shown by the recent work of Hubert (1978), McPherson (1979), Bown and Kraus (1981) and Goldbery (1982).

The purpose of this chapter is to give a general review and discussion of the character and implications of the calcretes developed so plentifully within the Lower and the Upper Old Red Sandstone facies of the Anglo-Welsh area in southern Britain. The claim (Allen, 1974a, 1974b) that these accumulations of carbonate minerals are primarily pedogenic is made essentially on the basis of (1) their repeated occurrence in vertical profile according to a simple general pattern, and (2) the repetition from profile to profile of the same (or largely the same) set of features, some microscopic and other macroscopic, which have been closely matched in calcretes forming either today or in the recent past (Netterberg, 1967, 1971; Goudie, 1973, 1983; Reeves, 1976; Milnes and Hutton, 1983). The lack of reports from the Anglo-Welsh area of catenas involving calcretes may cause some neopedologists either to suspend judgement on or even to dismiss these broadly 360–410 Ma old soils, but the fact that the other two criteria are satisfied is to the palaeopedologist a *prima facie* ground for the interpretation offered. On the basis of their presently observable characteristics—a set limited by intraformational erosion and by protracted diagenesis—these Old Red Sandstone paleosols may tentatively be classified largely amongst the Aridisols and Vertisols. Further work on them is necessary, particularly in Scotland and Ireland, and it is probable that other kinds of soil material will as a consequence be detected. However, it seems unlikely that the broad interpretation so far advanced will require other than minor modification.

## STRATIGRAPHICAL CONTEXT OF THE CALCRETES

The stratigraphy of the Old Red Sandstone facies at outcrop in the Anglo-Welsh area is outlined in Figure 1, based on Allen's (1977) review and later contributions by Allen and Williams (1978, 1981),

Squirrell and White (1978), Allen *et al.* (1981, 1982), and Williams *et al.* (1982). Details of thickness, lithology and evidence for correlation should be sought in these sources.

The Lower Old Red Sandstone, ranging from the Pridoli (late Silurian) to possibly the Emsian (late Lower Devonian), is an upward-coarsening red-bed succession some 2–4 km thick. Except in south-west Wales, where a thin fluvial sequence fills a palaeovalley, the lowermost beds are thin shallow-marine sandstones and, except locally (mid Wales), subordinate mudstones. The overlying Pridoli and early Gedinnian rocks are mudstones with very subordinate sandstones. A restricted marine fauna typifies the earlier of these beds, which on the whole appear to represent mixed marine and fluvial influences and extensive coastal mudflats. The overlying beds are wholly fluvial, consisting of intraformational conglomerates, sandstones and mudstones in various kinds of erosively-based and commonly upward-fining sequence (e.g. Allen, 1974b, 1983; Tunbridge, 1981b). Upward from the base of these fluvial measures the sandstones become progressively coarser grained and thicker relative to the mudstones until, in the upper part of the Woodbank Group, Brownstone Group, Brownstones, and Cosheston Group, mudstones disappear except as a ghost facies (intraformational debris) and exotic pebbles manifest themselves abundantly.

The Upper Old Red Sandstone (Frasnian–earliest Tournasian) is an order of magnitude thinner than the Lower division and at most localities passes upward without a break into marine Carboniferous rocks. In South Wales, and possibly in the Clee Hills, a mid Famennian disconformity is present within the beds. The rocks below the disconformity in central South Wales are shallow-marine, and the Gupton Formation in south-west Wales may possibly be of this origin.

The Old Red Sandstone in Anglesey is of uncertain age (mid Silurian to early Carboniferous) but, on strong lithological grounds, may be correlated to the Gedinnian formations of the Welsh Borders and South Wales.

Calcretes occur in all but the most marine portions of the Lower Old Red Sandstone succession, typically within mudstones, but in places either within or as a capping to sandstones. They are first seen in the Temeside Shale Formation, in a close and repeated association with tidal-flat sandstones and mudstones bearing a restricted marine invertebrate fauna. Calcrete profiles, many of a thick and advanced type, occur throughout the Pridoli and early Gedinnian mud-dominated part of the succession (Allen and Williams, 1979), culminating in the great concentration of thick calcretes known as the '*Psammosteus*' Limestones. King (1934) recognized that the '*Psammosteus*' Limestones

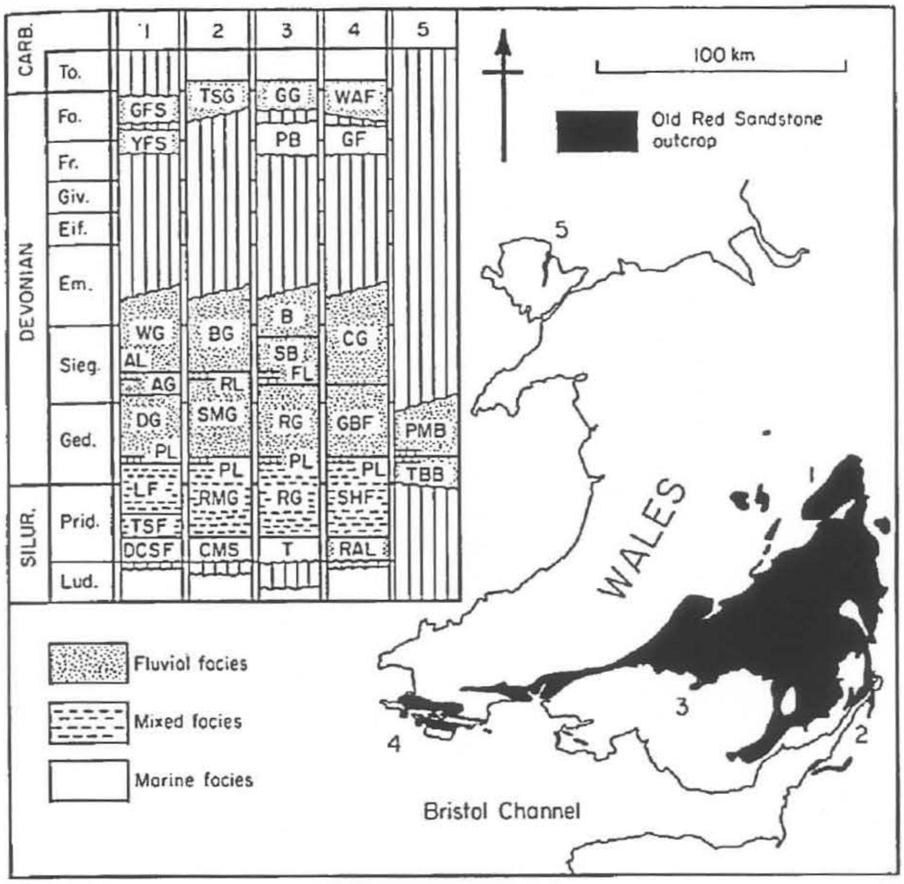



Figure 1. Stratigraphical outline of the Old Red Sandstone facies at outcrop in the Anglo-Welsh area (sources listed in text). Key to stratigraphic columns: 1—Clee Hills; 2—Forest of Dean and area south-east of the R. Severn; 3—Central South Wales; 4—South-west Wales; 5—Anglesey. Key to lithostratigraphic units: AG—Abdon Group; AL—Abdon Limestone Formation; B—Brownstones; BG—Brownstone Group; CG—Cosheston Group; CMS—Clifford's Mesne Sandstone; DCSF—Downton Castle Sandstone Formation; DG—Ditton Group; GBS—Gelliswick Bay Formation; GG—Grey Grits; LF—Ledbury Formation; PB—Plateau Beds; PL—'*Psammosteus*' Limestones; PMB—Porth y Mor and Traeth Lligwy beds; RG—Red Marl Group; RL—Ruperra Limestone; RMG—Raglan Marl Group; SB—Senni Beds; SHF—Sandy Haven Formation ('*Psammosteus*' Limestones inserted from a correlative to the south); SMG—St. Maughan's Group; T—Tilestones; TBB—Traeth Bach and Bodafon beds; TSF—Temeside Shale Formation; TSG—Tintern Sandstone Group (with Quartz Conglomerate); WAF—West Angle Formation; WG—Woodbank Group; YFS—Yellow Farlow Sandstone.

could be traced as a facies throughout the Welsh Borders and South Wales; they appear to be represented also in Anglesey (Allen, 1965). In the more southerly parts of this tract, for example, in south-west Wales (Dixon, 1921; Allen, 1974a; Allen and Williams, 1979) and the Forest of Dean (Allen, 1974a; Allen and Dineley, 1976), the facies

is 40–50 m thick and consists predominantly of mudstones (with calcretes) but with few sandstones. Gradually northward the facies roughly doubles in thickness, as fluvial sandstones in upward-fining sequences become more numerous and appear at progressively lower horizons (Allen, 1974b; Allen and Williams, 1979). White's (1950a,b) contention that the '*Psammosteus*' Limestones facies is diachronous is difficult to accept, since it is in these fluvial sandstones that the vertebrates used for dating are preserved. Calcretes are no less frequent above than below the '*Psammosteus*' Limestones, except in the sand-dominated late Siegenian and Emsian measures, but are generally speaking thinner and less well-developed. An important exception, representing a stratigraphically higher concentration of calcretes, occurs in the mid Siegenian beds. Massive calcretes are developed near the top of the St. Maughan's Group in the Forest of Dean (Allen and Dineley, 1976), and approximate equivalents appear to be the Ruperra Limestone and other named beds near Monmouth and Newport (Welch and Trotter, 1961; Squirrell and Downing, 1969), what have been called the Ffynnon Limestones of the Black Mountains (Ball and Dineley, 1961), and the Abdon Limestone Formation of the Clee Hills (Allen, 1974b).

Calcretes are less prevalent and not as well developed in the Upper Old Red Sandstone, in which they are restricted to the fluvial measures. They are best seen in the West Angle Formation (Williams *et al.*, 1982) of south-west Wales but are also present in the Tintern Sandstone Group and its correlatives (Pick, 1964) of the Forest of Dean area and the Grey Farlow Sandstone of the Welsh Borders.

Mesozoic and younger strata conceal an extensive development of the Old Red Sandstone facies in central and eastern England. Nodular mudstones, possibly including calcretes, are described from an Emsian fluvial facies cored at Canvey Island in the Thames Estuary (Smart *et al.*, 1964). Unquestionable calcretes are present in some abundance in the Famennian fluvial rocks penetrated at Merevale No. 2 east of Birmingham (Taylor and Rushton, 1972).

## FIELD CHARACTERISTICS OF THE CALCRETES

### Profiles

In terms of vertical profile, most of the calcretes can be assigned to one of three intergrading types (Figure 2). Type A profiles, with affinities to Gile's stage II (Gile *et al.*, 1966) and Goudie's (1983) nodular calcrete, range from a few decimetres to between 2 and 3 m in thickness, and consist of scarce to common, diffuse and irregular to crudely cylindrical, rounded or discoidal calcite glaebules (Brewer, 1964) set in

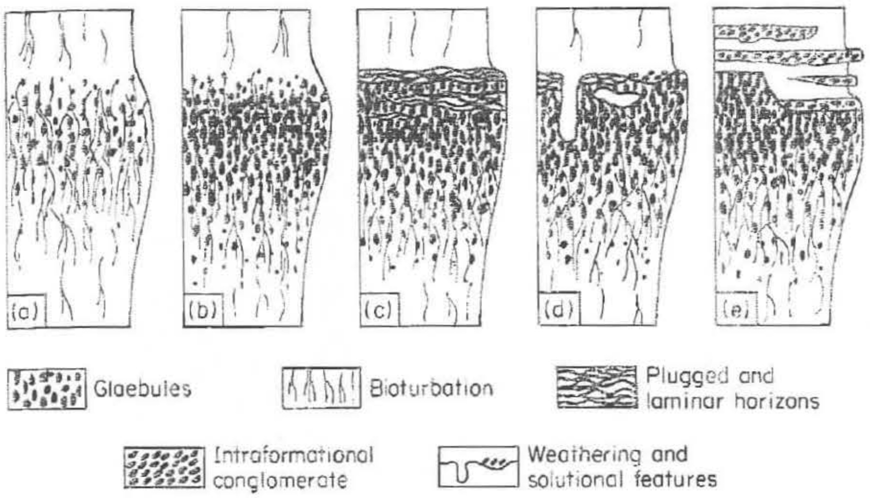



Figure 2. Schematic calcrete profiles (complete and truncated). (a) Type A. (b) Type B. (c) Type C. (d, e) Modified profiles.

the host sediment (Figures 3, 4). Equant to bedding-normal glaebules tend to be restricted to mudstone hosts (Figures 3, 4(a)), whereas discoidal ones, aligned parallel with the lamination, are normally found only in the sandstones (Figures 4(c), (d)). The glaebules vary from a few millimetres to many centimetres across or long, and may

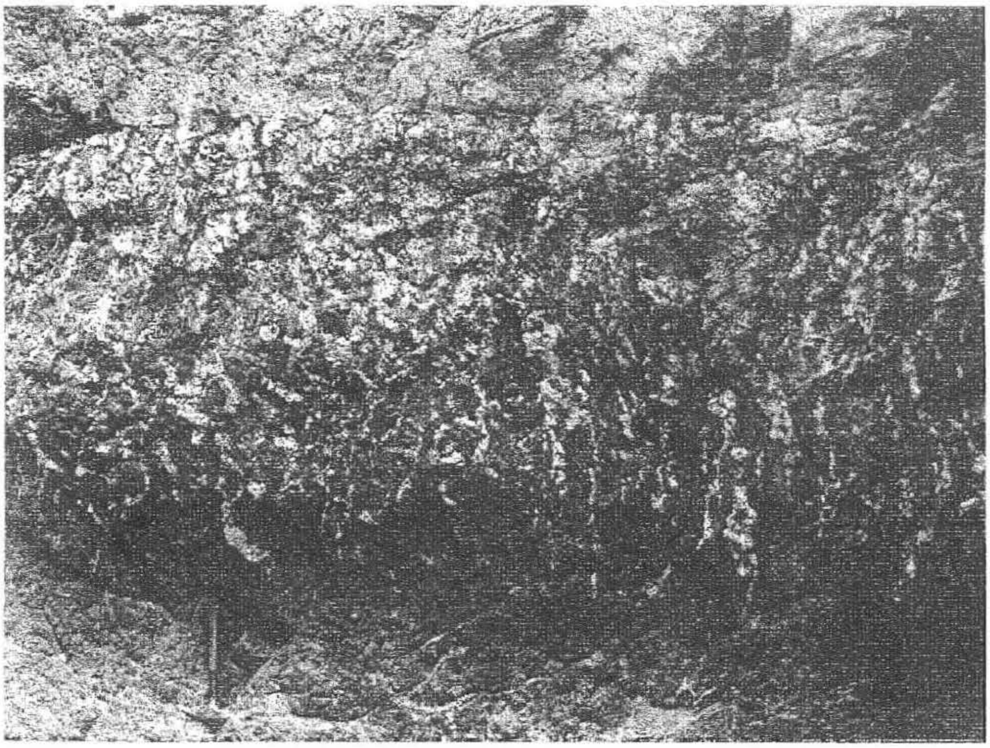


Figure 3. Truncated type A profile bordering on type B, Freshwater West Formation, Greenala Point (British National Grid Reference SS 008 967). Geological hammer for scale.

locally fuse with each other. Untruncated profiles (comparatively rare) show the glaebules to have their highest density about mid-way up or toward the top of the calcrete. Closely resembling Gile's type III profiles, and Goudie's (1983) honeycombe calcretes, are profiles of type B. These locally attain 15 m in thickness (Figure 5(a)) but are generally between 1 and 5 m thick (Figure 5(b)). They are characterized by a gradual upward increase in glaebule size and density, from small and scarce near the base, to large and partly fused at intermediate levels, to closely packed and extensively joined at the top (Figures 5, 6). Particularly where the host sediment is silty or sandy (Figure 6(a)), a three-dimensional meshwork of irregular calcite veins may occur in the middle and lower parts of the profile. Glaebules near the top are in many cases so large and close-packed as to be crudely prismatic and partly separated by discontinuous mudstone screens (Figure 7). Type C profiles compare well with the stage IV calcretes of Gile *et al.* (1966) and Goudie's (1983) hardpan and laminar calcretes. They are similar to profiles of type B except that, at and near the top, there is evidence

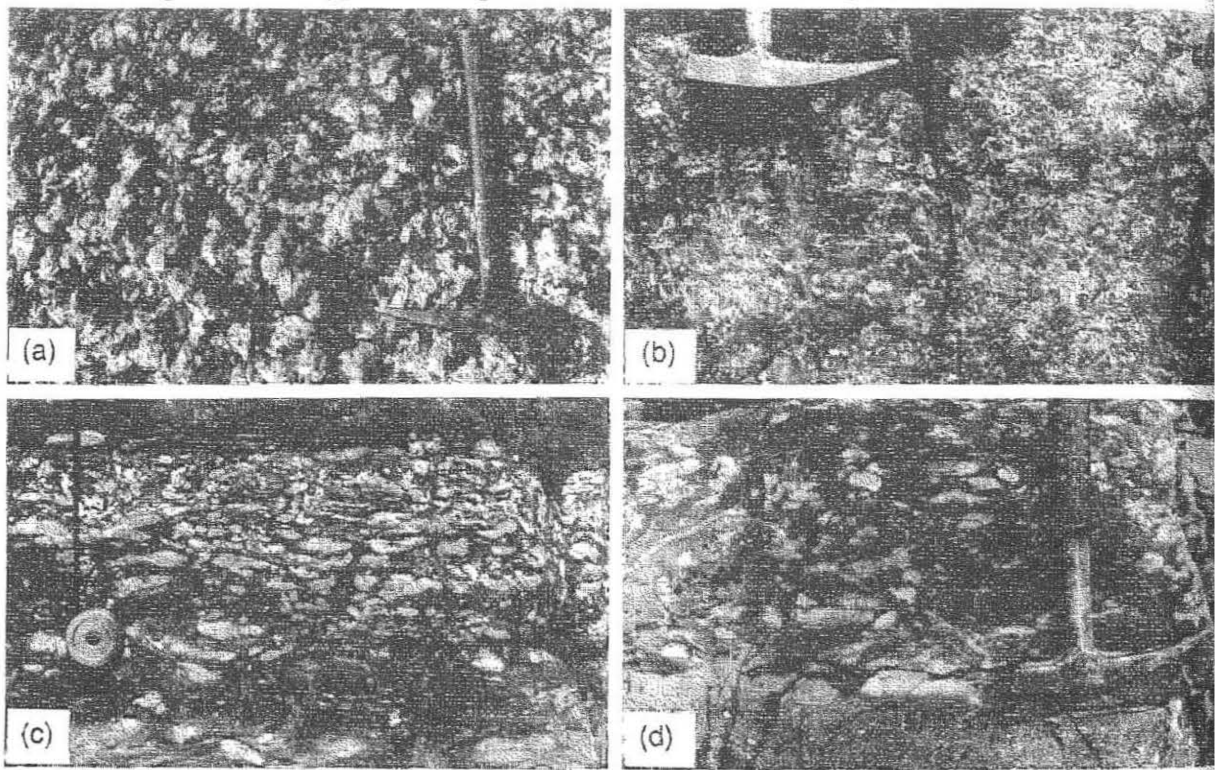
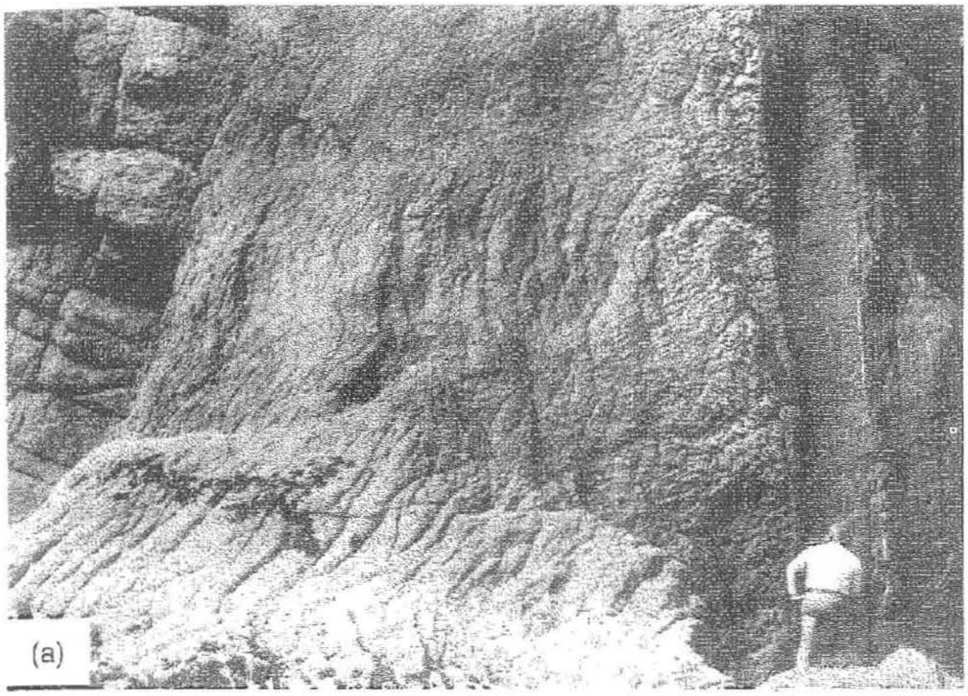
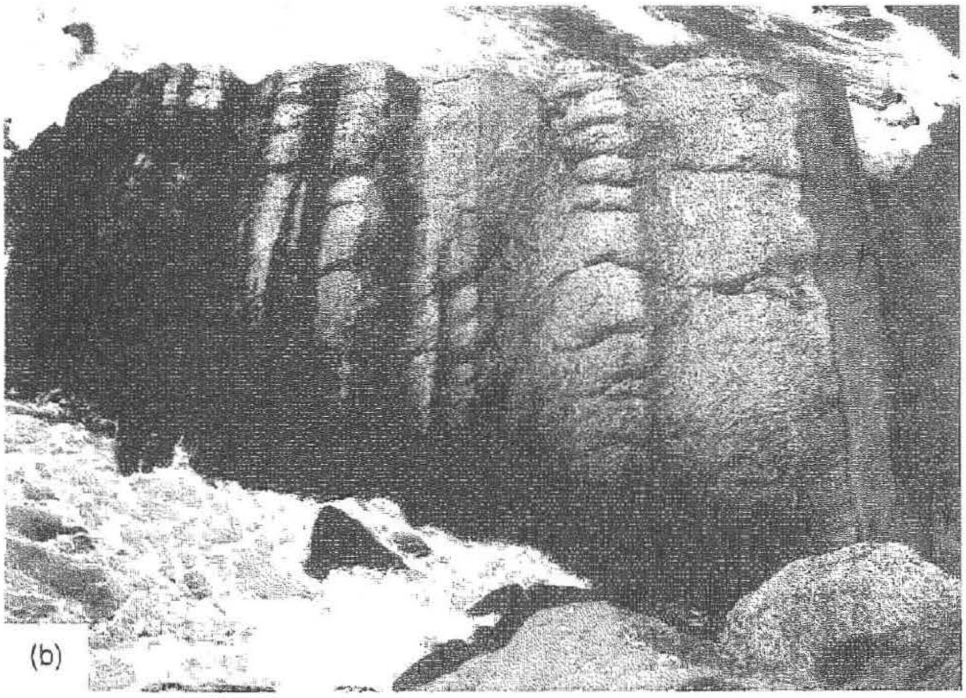



Figure 4. Variation amongst glaebules in calcrete profiles. (a) Equant to bedding-normal glaebules, Red Marl Group, Llanstephan (SN 350 099). (b) Very irregular glaebules with some subhorizontal calcite vein fillings and carbonate-filled tubes, West Angle Formation, West Angle Bay (SM 850 038). (c) Bedding-parallel glaebules in very fine sandstone, Moor Cliffs Formation, south of Angle (SM 867 008). (d) Equant to bedding-parallel glaebules, silty sandstone, West Angle Formation, West Angle Bay (SM 850 038). Geological hammer and pocket measuring tape for scale.



(a)



(b)

Figure 5. Type B calcretes. (a) Truncated profile (younging to right) overlain by thin patches of intraformational conglomerate, Moor Cliffs Formation, Presipe (SS 069 969). Note wave-like pseudoanticlines and fanning of glaebules (rotate photograph). (b) Calcrete profiles (mainly type B) in the '*Psammosteus*' Limestones, Moor Cliffs Formation, Chapel Point, Caldey Island (SS 141 958). Beds young to right and thickest profile attains about 6 m. Note pseudoanticlines in the two youngest profiles.

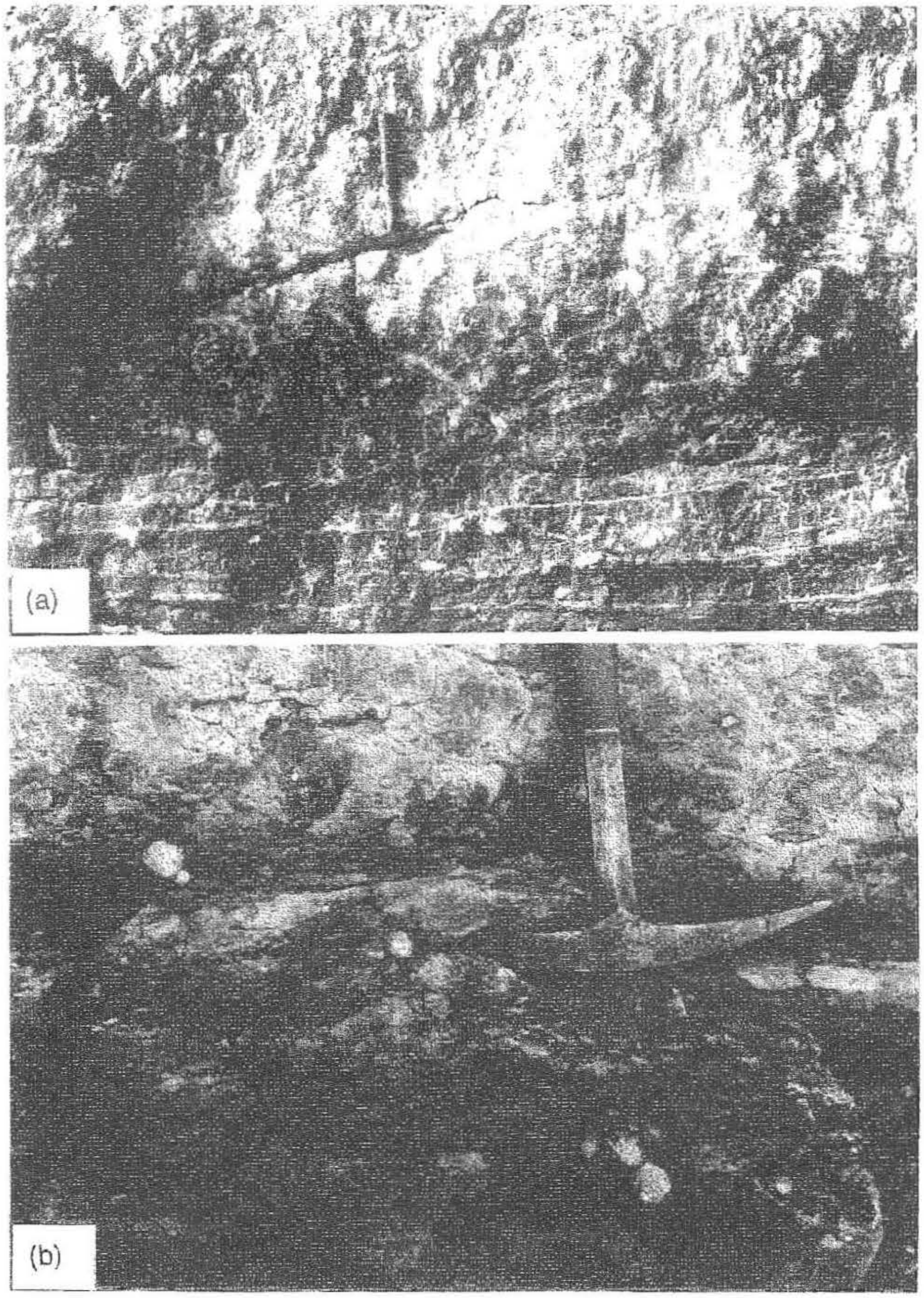



Figure 6. Type B calcretes. (a) Red Marl Group, Llanstephan (SN 349 099). Geological hammer for scale is at horizon of maximum glaebule density. Note system of combined horizontal and vertical calcite veins in lower half of profile. (b) Advanced type B profile with local type C features, West Angle Formation, West Angle Bay (SM 867 008). Geological hammer for scale.

for the repeated fracture and rebinding by crystallaria (Brewer, 1964) of extensively fused nodules, and the development of substantial horizontal sheets of irregularly laminated to mammilar crystallaria (Figure 8).

Stratigraphically, the three types of profile are unequally distributed.

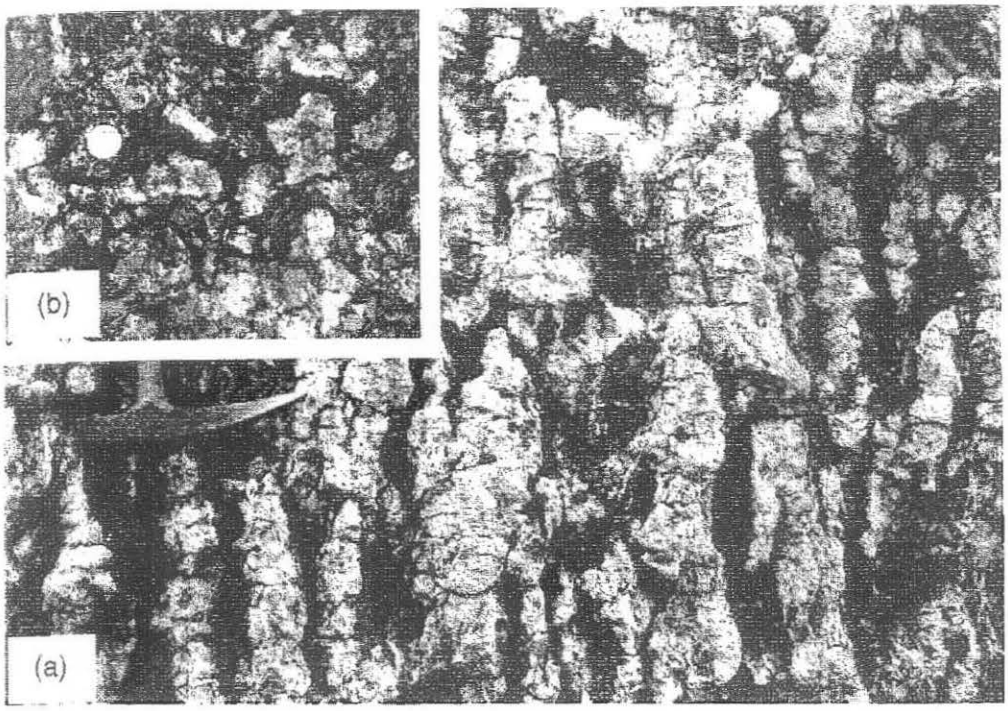



Figure 7. Details of subprismatic glaebules in a type B calcrete (11 m thick), '*Psammosteus*' Limestones, Raglan Marl Group, Lydney (SO 654 021) in (a) vertical profile (note local fusion of glaebules and thin mudstone screens; geological hammer for scale) and (b) bedding-parallel view (coin for scale 0.028 m across).

In the Lower Old Red Sandstone, type A profiles occur throughout the succession and are perhaps most representative of the fluvial measures above the '*Psammosteus*' Limestones. Type B profiles are typical of the Pridoli and early Gedinnian calcretes, including those of the '*Psammosteus*' Limestones. Profiles of type C are comparatively rare, being restricted to the Pridoli and early Gedinnian mud-dominated part of the succession, and to the mid Siegenian calcretes (e.g. Abdon Limestone, Ffynnon Limestones) developed in sandstone hosts. The highest substantial calcrete is developed in the Brownstones above the Pebbly Beds (Squirrell and White, 1978) in Central South Wales. Profiles of all three kinds are present in the Upper Old Red Sandstone, and particularly in equivalents of the Tintern Sandstone Group (Pick, 1964) and the West Angle Formation. The calcretes at this level tend to be much thinner than their counterparts in the Lower Old Red Sandstone and are developed in sandier hosts.

## Lateral Extent

There can now be little doubt that individual calcretes in the Old Red Sandstone are laterally very extensive, although the direct evidence for this is not surprisingly meagre, given the nature of the exposures

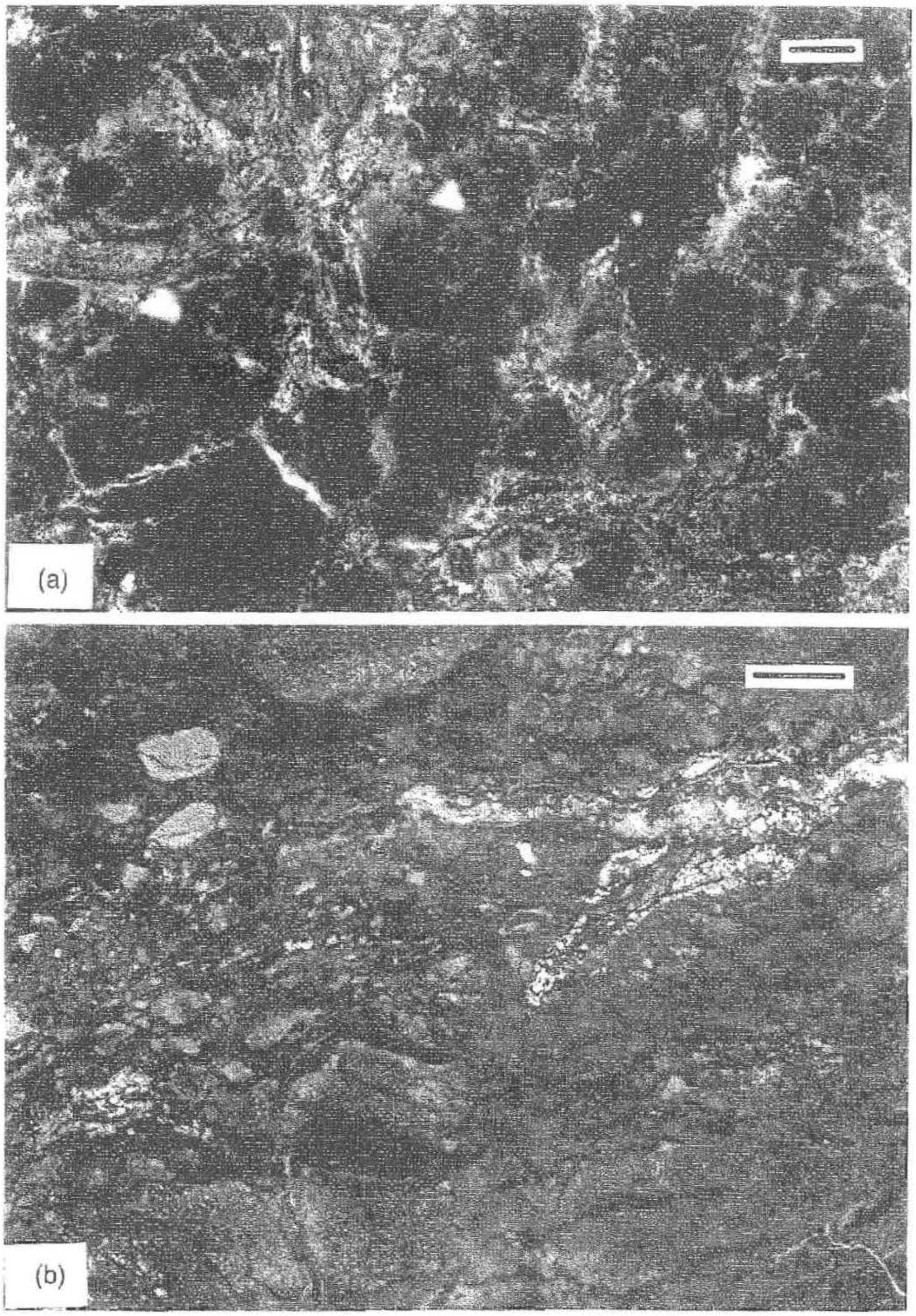



Figure 8. Vertical polished surfaces in type C calcretes. Scale bars 0.01 m long. (a) '*Psammosteus*' Limestones, Ditton Group, near Ludlow (SO 511 786). Fused glaebules are separated by screens of calcite-cemented quartz sand, and the mass is extensively cut by both horizontal and vertical crystallaria. (b) Abdon Limestone Formation, Abdon Group, near Ludlow (SO 587 868). A complex of very subordinate glaebules with predominant internal, coating, and cross-cutting crystallaria from a laminar horizon. The most extensive crystallaria are sub-horizontal.

available. Only at a few places can calcretes be walked out for any distance. One of these is on the cliffs east of Freshwater East (south-west Wales), where thick profiles of type B can be traced laterally for distances of up to 800 m (Williams *et al.*, 1982). A calcrete 11 m thick within the '*Psammosteus*' Limestones can be walked out a similar distance at Lydney in the Forest of Dean (Welch and Trotter, 1961). Using resistivity methods, Dineley and Gossage (1959) were able to trace calcretes for up to 700 m laterally at a similar stratigraphic level in the Clee Hills. The Abdon Limestone of the same area has been mapped over an extent of roughly 100 km$^2$ without a significant alteration in character (Allen, 1974b), and so must originally have been part of a much more extensive sheet (embracing the Forest of Dean and south-east Wales?).

Convincing evidence that individual calcretes are as extensive as the preceding observations imply comes from the Pridoli rocks of south-west Wales, where Allen and Williams (1982) were able to correlate with precision numerous thin airfall tuffs just a few metres apart stratigraphically over an area measuring approximately 12 by 35 km. The mudstones between the tuffs include type A and B calcretes, some of which could be recognized over the whole area, except where cut out by an erosively-based sandstone complex.

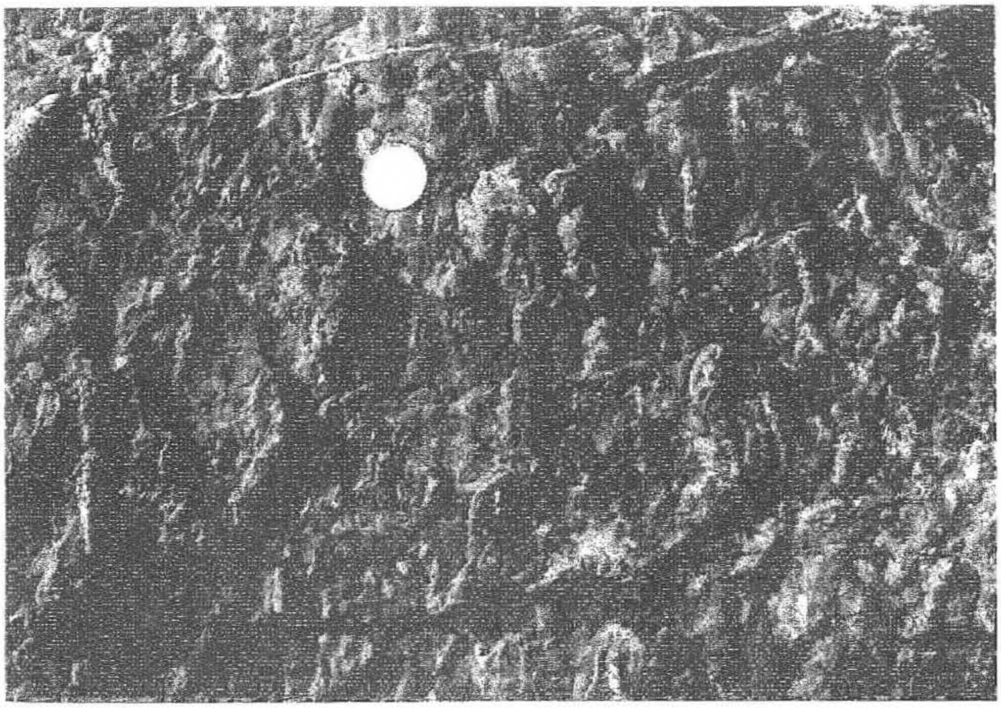


Figure 9. Upright calcite-filled tubes and small glaebules in type A calcrete, Red Marl Group, Llanstephan (SN 349 099). Coin for scale 0.028 m across.

### Bioturbation

The mudstones of the Old Red Sandstone are characteristically unlaminated, massive and blocky-fracturing. These features, during Pridoli and early Gedinnian times, resulted from organic destratification contemporaneous with deposition, to judge from the faeces-strewn mudstone surfaces repeatedly smothered by the airfall tuffs (Allen and Williams, 1981, 1982), and the same explanation may largely apply throughout the Old Red Sandstone. Conventional trace fossils in an as yet poorly assessed variety are also plentiful in the Old Red Sandstone facies, and two apparently distinct forms are abundantly present in association with the calcretes, especially those older than mid Siegenian.

One kind, typically surrounded by a diffuse halo of blue mudstone or sandstone, consists of an irregular, downward-branching (once or twice) tube, several to many decimetres long and a few millimetres across with uneven, longitudinal corrugations on the wall. The fill may be either calcite or mudstone. Whether these structures record plant or animal activities remains uncertain (Allen and Williams, 1982). The other kind of trace fossil (Figure 9) is a cylindrical, straight to slightly winding, smooth-walled, subvertical tube up to 8 mm wide and many centimetres long. The fill varies from mud or silt, with evidence for back-packing, to calcite frequently serving as the nucleus of a subsequent glaebule. These structures almost certainly have an invertebrate origin. The striking abundance of these two expressions of bioturbation in the calcretes points to the marked biological activity of the Old Red Sandstone soils, if not throughout the development of each profile then certainly in the earlier stages.

### Fracture Systems

Allen (1973, 1974a,b) described patterns of fold-like fractures from certain Lower Old Red Sandstone calcretes, and compared them in both scale and origin to the *gilgai* widely reported from certain clay-rich alluvial soils in present-day warm dry regions (Hallsworth and Beckmann, 1969). Further work has shown that a rather wider range of fracture geometries is represented in Lower Old Red Sandstone calcretes and that perhaps the majority of profiles display one or more of these patterns, which appear schematically in Figure 10. Fracture patterns are rare in the Upper Old Red Sandstone calcretes, developed in generally sandier sediments than in the Lower division. Similar structures have subsequently been found to occur in other ancient fluvial formations with paleosols (e.g. Goldbery, 1982; Wright, 1982).

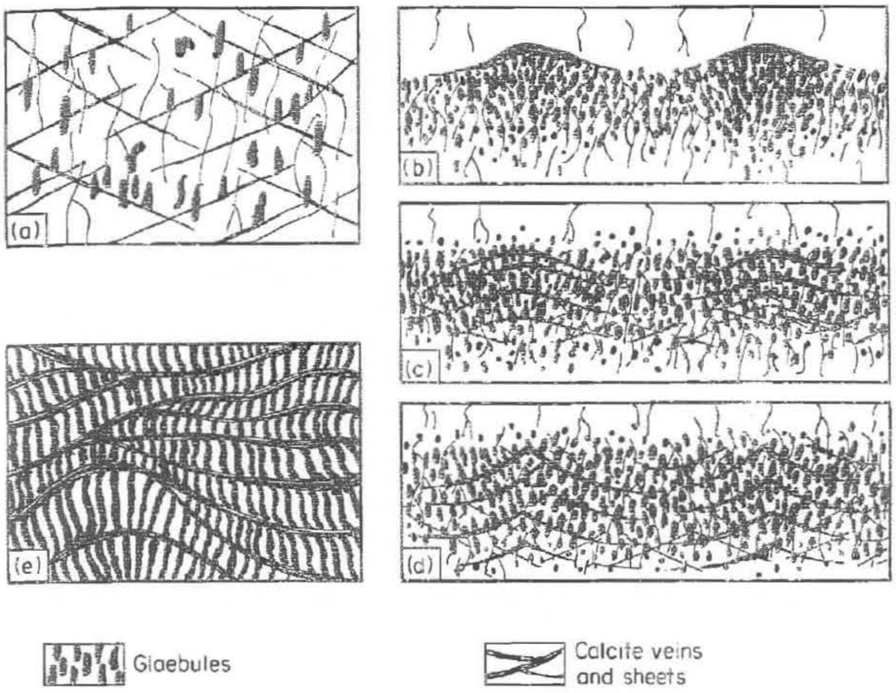



Figure 10. Schematic representation of fracture systems in Old Red Sandstone calcretes. (a) Conjugate planar fractures. (b) Pseudoanticlines expressed by an undulose profile top and internal glaebule fans. (c) Pseudoanticlines in the form of rounded calcite-filled fractures with glaebule fans. (d) Pseudoanticlines expressed by glaebule fans and calcite-filled fractures in the form of pointed folds. (e) Pseudoanticlines with thick calcite-mud fracture-fills and distorted glaebules.

Many profiles of type A display in vertical profile an open meshwork of extensive, conjugate, slickensided fractures (Figure 10(a)), which may be either unfilled or sealed with millimetre-scale calcite veins (Figure 11(a)). The fractures vary from planar (the majority) to weakly concave up, and lie at 20–25° from the general bedding. There is no spatial variation in the distribution of dip-angles on the fractures.

A very few profiles of type B (advanced) and type C reveal a regularly undulose top on a scale of several metres beneath which the glaebules show a systematic variation in both size and density as well as orientation (Figure 10(b)). This type of structure, for which the term pseudoanticline (Watts, 1977) is appropriate, is strongly suggestive of *gilgai* and particularly recalls the variety involving puffs (mounds) and shelves (Allen, 1974a).

Much more common in profiles of both types A and B are the fold-like (wavelength 2–10 m) distributions of glaebules and calcite-filled slickensided fractures shown schematically in Figure 10(c), (d). The first variety displays, in two-dimensional profile, fan-like arrangements of glaebules (cf. cleavage fans) and extensive calcite-filled fractures in

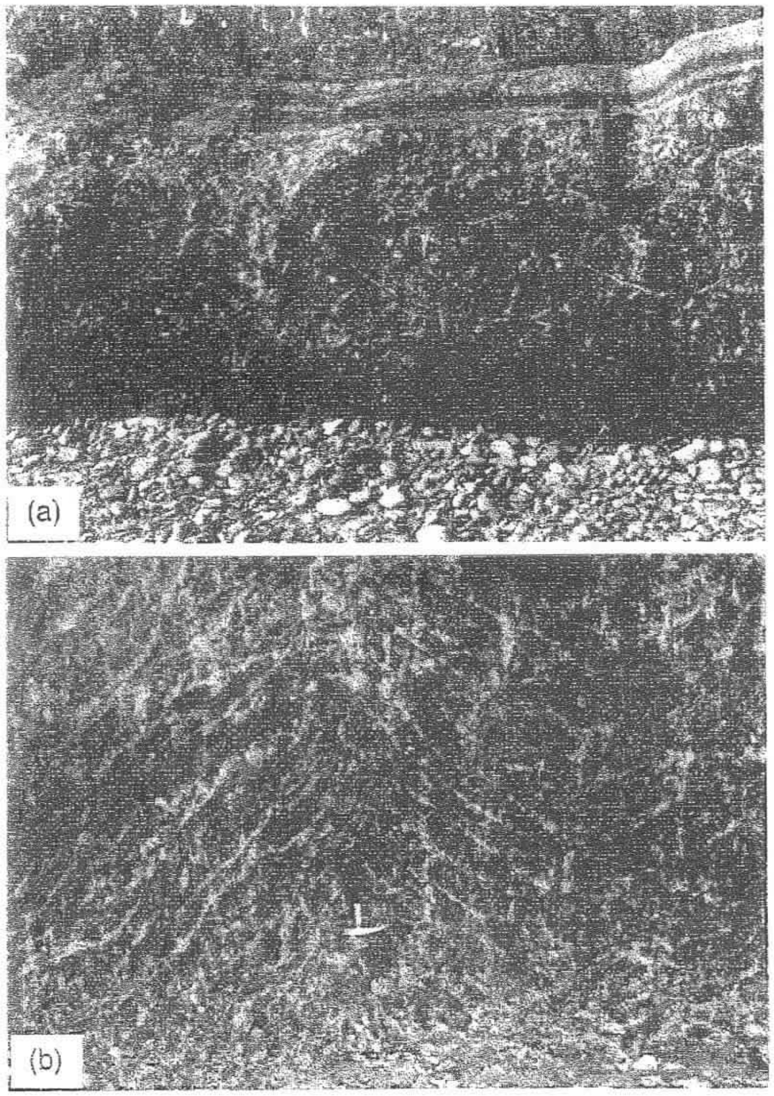



Figure 11. Fracture systems in calcrete profiles. Geological hammer for scale. (a) Type A calcrete with truncated top and conjugate planar to weakly concave calcite-filled fractures, Red Marl Group, Llanstephan (SN 349 099). (b) Pseudoanticlines (see Fig. 10d) in a type B calcrete 11 m thick, '*Psammosteus*' Limestones, Raglan Marl Group, Lydney (SO 654 021).

the form of rounded 'synclines' and less rounded 'anticlines'. The second variety differs from the first in showing sharply pointed anticlines and a more obvious severance and/or displacement of glaebules across the fractures (Figure 11(b)). The three-dimensional geometry of these fracture systems has not yet been fully explored, but their general form can be readily appreciated from certain favourable cliff exposures, east of Freshwater East and at Greenala Point near Stackpole, both in south-west Wales. Most of the fractures prove to be roughly bowl-like, with the slickensides radiating upward away from the axis of the concave-up bowl. These fractures become less strongly developed downward in the calcrete profiles and may be accompanied,

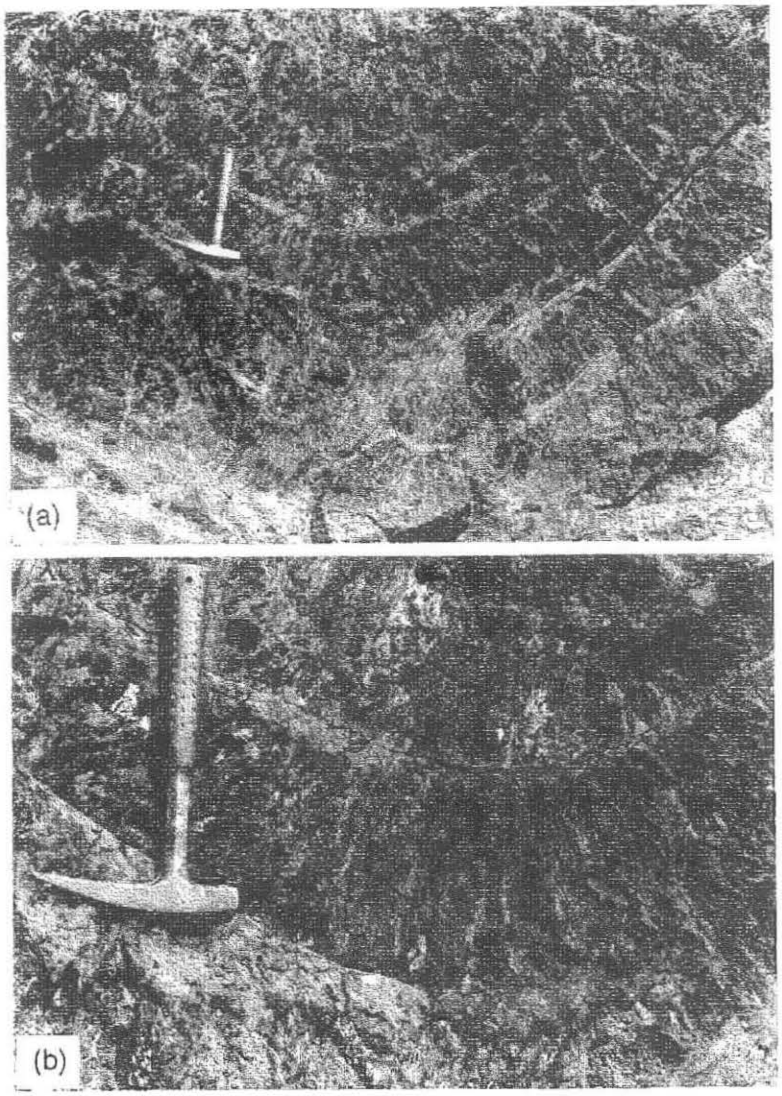



Figure 12. General view (a) and close-up (b) of pseudoanticlines defined by thick calcite-mud fracture fillings (note open cracks) and distorted glaebules (partly weathered out), Moor Cliffs Formation, south of Angle, (SM 867 009). Geological hammer for scale.

at intermediate and low levels, by systems of less conspicuous planar cracks (Figure 10(a)).

The thick types B and C profiles developed in the Pridoli and early Gedinnian mudstones, especially of south-west Wales, display a fifth type of pseudoanticlinal structure (Figure 10(e)). The calcrete is divided up into large concavo-convex to corrugated lens-like masses by curved centimetre-thick sheets composed of irregularly interlaminated calcite and terrigenous mud (Figures 5(a), 12). The glaebules, closely packed between mudstone screens and almost invariably highly elongate, in many places bend toward the sheets in a manner reminiscent of strata dragged against a fault (Figure 12(b)). An open crack may be present at the centre of each sheet.

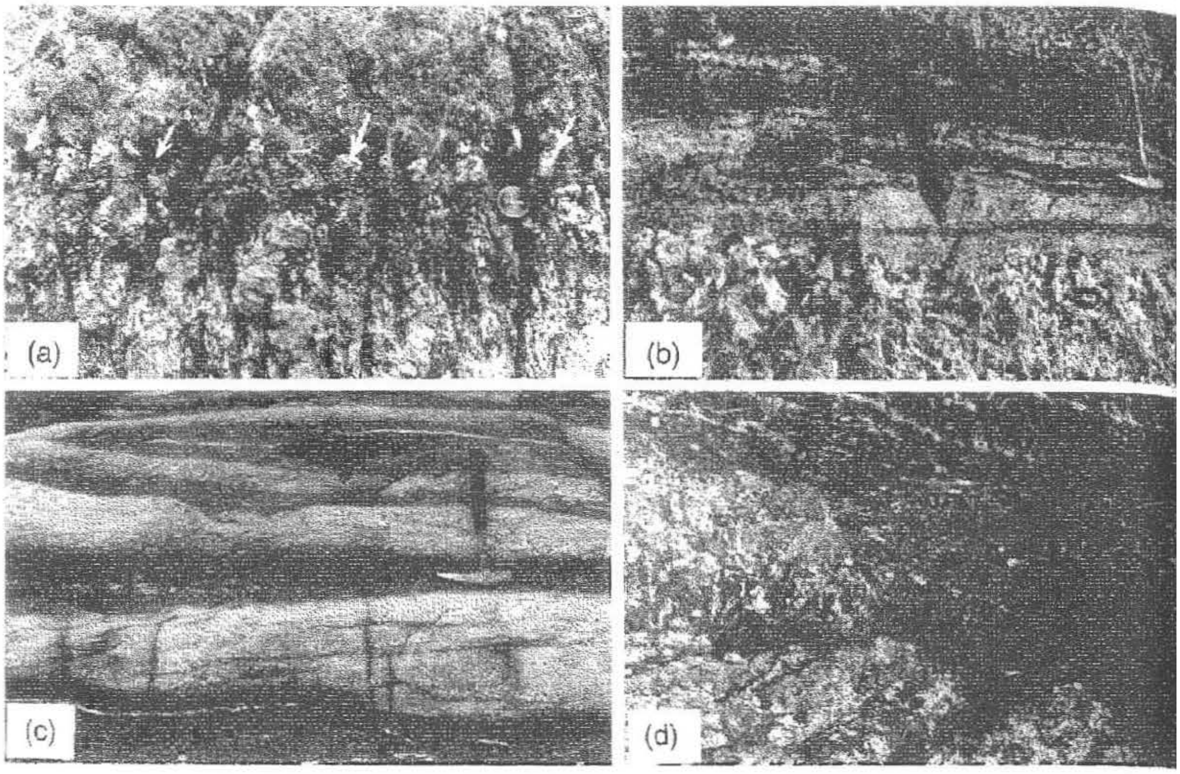



Figure 13. Features of the eroded tops of calcrete profiles. Geological hammer and camera lens-cap for scale. (a) Calcrete profile overlain by several centimetres of intraformational pebble conglomerate (arrowed) and a (calcretized) mudstone, Freshwater West Formation, Greenala Point (SS 008 967). (b) Interbedded mudstones and calcrete conglomerates overlying the uneven, eroded top of a calcrete in the '*Psammosteus*' Limestones, Moor Cliffs Formation, Caldey Island (SS 143 958). (c) Part of a thick complex of interbedded mudstones and intraformational conglomerates overlying a calcrete, Red Marl Group, Llanstephan (SN 350 099). (d) Pebbly mudstone infilling channeled top of calcrete, '*Psammosteus*' Limestones, Moor Cliffs Formation, Caldey Island (SS 143 958).

## Profile Truncation

A substantial proportion of calcrete profiles, especially the thicker ones, are sharply truncated upward by a surface of either erosion (Allen and Williams, 1979) or, much less commonly, weathering.

Weathered tops, as can be seen at Lydney in the Forest of Dean, are slightly uneven surfaces, with the hollows infilled by a mud-bound rubble of slightly disturbed angular calcrete fragments ranging downward to millimetre-scale crumbs (Figure 2(d)). The bosses between, instead of being irregular, are in some places smoothly curved, as if rounded by solution. Features closely resembling vertical solution pipes and cavities have been seen to range downward for a few decimetres from the sharp top of one profile.

Eroded tops to calcrete profiles are much more common (Figure 2(e)). The thick profile shown in Figure 5(a) has a sharp, even top overlain by patches up to a few centimetres thick of an intraformational conglomerate formed of sorted and rounded calcrete debris (see also Figure 13(a)). In many instances this kind of overlay is a mere single clast thick, and is easily overlooked in the field, particularly where access is difficult. A fairly common type of overlay is a complex as thick as 2 m of interbedded mudstone and intraformational conglomerate units resting on an even to slightly irregular surface (Figure 13(b), (c)). Locally these conglomerates are internally channelled. Some conglomerate units are well sorted and internally bedded, with a sparry calcite cement, whereas others are ill-sorted and poorly if at all stratified internally, mud serving to bind the clasts. Quartz sand grains are invariably lacking from the conglomerates and beds of quartzose sandstone do not figure amongst the interbedded units of conglomerate and mudstone. Another feature which distinguishes intraformational conglomerates in this setting from those associated with upward-fining quartzose sandstone complexes is the absence of vertebrate remains (Allen and Williams, 1979). Locally the eroded tops of calcretes reveal broad, shallow flat-bottomed channels (Figure 13(d)).

## MICROSCOPIC FEATURES OF THE CALCRETES

Compositionally, the calcrete glaebules and massive limestones consist of carbonate minerals together with a variable quantity of quartz, feldspar, rock fragment and clay-mineral particles representative of the host sediment (Allen, 1965, 1974a,b). Except in the folded sequences of south-west Wales and Anglesey, where secondary ferroan dolomite and locally quartz are present in most calcretes, the profiles are dominated by low-magnesian calcite. Locally in the Welsh Borders a little barytes in the form of small rosettes is present, and in one calcrete profile in south-west Wales developed on a tuff (Allen and Williams, 1978), manganiferous and ferruginous nodules are recorded.

Thin sections, peels and polished surfaces reveal in the unrecrystallized calcretes from the Old Red Sandstone a wealth of textures and fabrics which have been described in detail (Allen, 1965, 1974a,b). Commonest is Brewer's (1964) undifferentiated crystic plasmic fabric, represented mainly by a lightly mottled mosaic of microcrystalline calcite accompanied by floating skeleton grains of quartz, feldspar, rock fragments, mica and clay minerals (Figure 14(a), (b)). Many of the skeleton quartz grains reveal corroded margins and some of the feldspars (rare from the start) have been entirely replaced by calcite. Exfoliation tends to be shown by cleaved or foliated skeleton grains

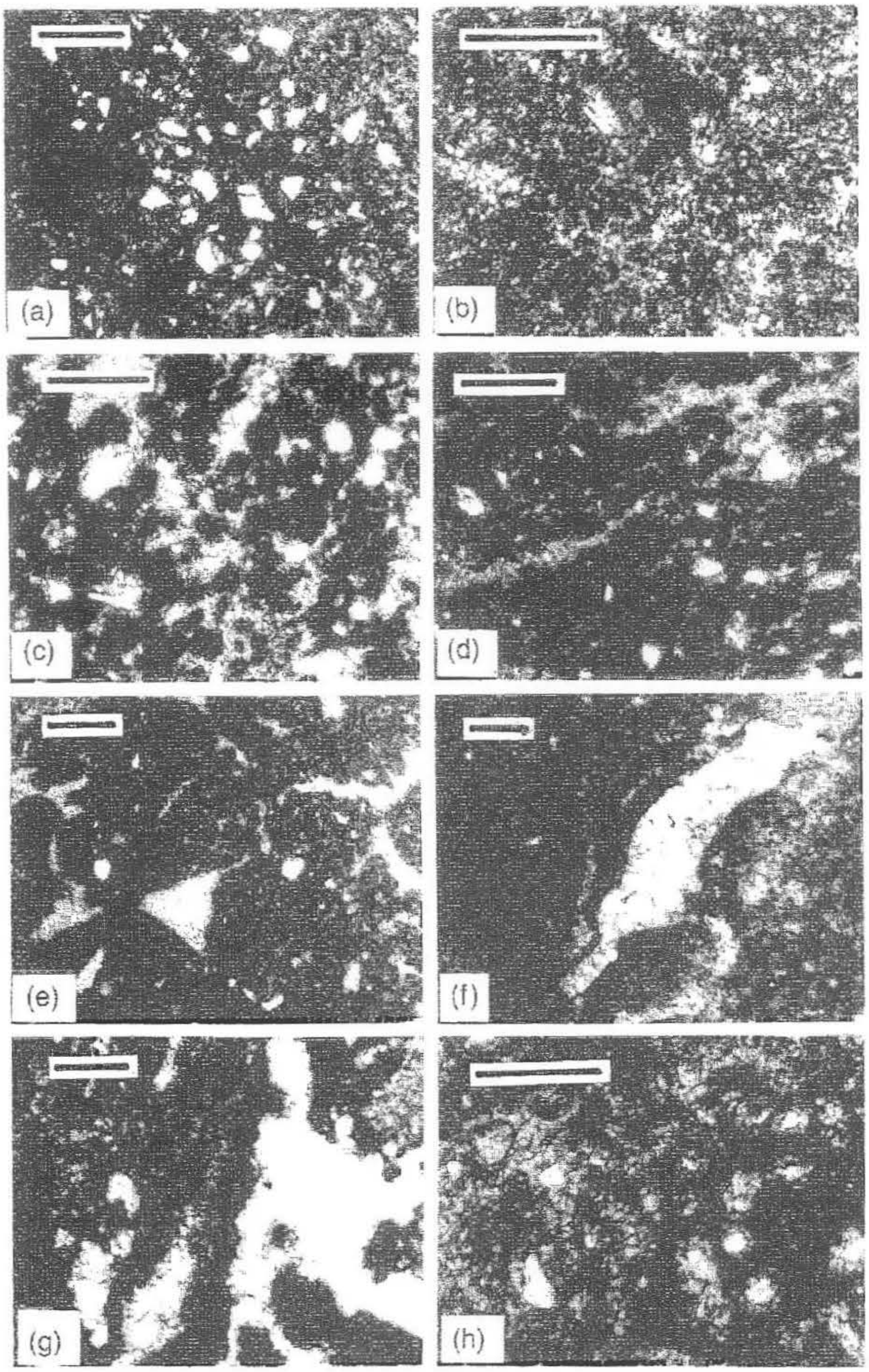



Figure 14. Microscopical features of calcretes in vertical section (stratigraphical top upward). (a) Undifferentiated crystic plasmic fabric. (b) Undifferentiated crystic plasmic fabric with fewer skeleton grains than (a). (c) Agglomeratic fabric. (d) Subhorizontal cracks. (e) Irregular to concavo-triangular crystallaria. (f) Laminated crystallaria lining an irregular void. (g) Complex crystallaria from a large void filling. (h) Skeleton grains with coarse-textured calcite halos. All samples from the Clee Hills. (a, h) Abdon Limestone (SO 587 868). (b, g) '*Psammosteus*' Limestones (SO 511 786). (c, d, e) Abdon Limestone (SO 581 848). (f) '*Psammosteus*' Limestones (SO 576 888). Scale bar 250 μm long.

(feldspar, mica, schistose and phyllitic rock fragments). Brewer's (1964) agglomeratic fabric is well represented in the glaebules and glaebular masses (Figure 14(c)). The voids preserved in these vary from subhorizontal systems of irregular hair-like cracks (Figure 14(d)), to irregular to concavo-triangular spaces between disrupted and partly displaced masses with a crystic plasmic fabric (Figure 14(e)), to septaria-like patterns (Allen, 1965, Pl. 13, Fig. 2), and finally large planar to irregular voids lined by laminated calcite crystallaria (Figure 14(f)). The largest voids of all were large open cracks, in many cases partly plugged by irregularly laminated to mammilar crystallaria before being broken open again (Figures 8, 14(g)). A final common fabric, a variant of Brewer's (1964) agglomeratic fabric and attributed to corrosion by some workers (e.g. Goudie, 1983), shows skeleton grains surrounded by a diffuse halo of microcrystalline calcite coarser textured than the bulk of the plasma (Figure 14(h)). Some smaller glaebules in Old Red Sandstone calcretes reveal a crudely concentric structure, but nothing comparable to the oolitic and pisolitic structures found in some Quaternary calcretes has so far been recorded.

## THE PEDOGENIC MODEL

The arguments for the pedological origin of the (Lower) Old Red Sandstone calcretes are set out fully and in detail elsewhere (Allen, 1973, 1974a,b), on the basis of an extensive direct and literature comparison with Quaternary calcretes and carbonate-bearing soils from many parts of the world. Only the main points need therefore be mentioned here, and details of the setting, character and age of these Quaternary examples used for comparison should be sought in the papers mentioned.

Essentially, the pedogenic model is adopted because the calcretes are closely comparable in scale, profile, macrostructure, composition and microfabric to many Quaternary pedogenic calcretes and carbonate-bearing soils, as reviewed by Netterberg (1967, 1971) and Goudie (1973), and more recently by Read (1976), Reeves (1976), Goudie (1983), and Milnes and Hutton (1983). The evidence points to the combined replacive and, more important, displacive introduction of calcite into deep alluvial sediments, particularly overbank muds but in many instances the upper levels of abandoned channel sand-bodies. The rocks are distinctly different from groundwater calcretes (Mann and Horwitz, 1979), principally in field development, although limestones and other calcareous sediments were exposed in the Old Red Sandstone source areas (Allen, 1974b); the amounts of plagioclase feldspar which reached the depositional site are far too small to have

afforded, by their decay, the quantity of carbonate minerals locked up in the calcretes. Hence the *per descensum* scheme of calcrete formation (Goudie, 1973, 1983) is preferred, with the carbonate entering the Anglo-Welsh area as windblown dust.

The widely and abundantly developed fracture systems are also consistent with a pedological origin for the calcretes. Bearing a marked resemblance to the larger cracks analysed by Knight (1980) from an Australian gilgaied soil, their shape, attitude and slickensided nature, combined with the evidence of displaced and curved glaebules, strongly suggests that they arose during the formation of the calcrete and in response to disruptive horizontal stresses (compressive) that substantially exceeded the vertical ones. As Allen (1973) pointed out, such a system of forces permitting upward relief could arise because of either or both (1) the displacive introduction of calcite to form glaebules, and (2) the swelling and shrinking of the clay-rich host in response to climatically controlled moisture variations. Probably both causes operated, although changing in relative importance as the calcrete profile matured. Moisture-related changes must be invoked where the glaebule density is low (e.g. Figure 11(a)), but the continued introduction of calcite is sufficient to explain the relative movement of large masses of soil-material suggested by the fractured carbonate-rich calcretes (Figures 5(a), 12). Significant for the former process is the fact that smectite clays, perhaps of penecontemporaneous volcanic origin (Parker *et al.*, 1983), occur in significant quantities in most of the Pridoli and earliest Gedinnian mudstones (e.g. Allen, 1974b). Watts (1977) in his discussion of pseudoanticlines has emphasized the considerable crystallization pressure exerted by calcite, but the displacive fibrous calcites he occasionally found have not so far been detected in the Old Red Sandstone calcretes.

## SIGNIFICANCE OF THE CALCRETES

### TIME-SCALES

Various lines of evidence (Gile, 1970, 1977; Baker, 1973; Goudie, 1973; Hay and Reeder, 1978; Shlemon, 1978), including radiocarbon dating (Gile, 1970; Williams and Polach, 1971; Williams, 1973), now known to have unreliable features (Callen *et al.*, 1983), have been used to age Quaternary calcretes absolutely and to estimate durations of pedogenesis. Visible carbonate accumulations can arise in as short a time as $10^2$ years. Well-developed profiles can be formed within as short a period as of the order of $10^3$ years or may necessitate pedogenosis over as long as $10^5$ or even $10^6$ years. The rate of calcrete formation thus appears to be highly variable and is probably dependent

on many factors, of which the rainfall regime (Gile, 1977) and the source and availability of carbonate may be the most important. Nothing directly is known of the durations of pedogenesis represented by Old Red Sandstone calcretes, but some constraints can be indicated by reference to stratigraphical evidence and our general understanding of the fluvial environment, the context of Old Red Sandstone pedogenesis. This provides a basis for looking at the implications of other time-scales.

As has been noted, there is within the Lower Old Red Sandstone some stratigraphical variation in the frequency, maturity, and mode of preservation of the calcretes. So far as the younger beds are concerned, the continued generation of calcrete soils within the depositional basin can be inferred only from the prevalence of calcrete debris in the intraformational conglomerates which floor the fluvial channel sandstones. Nonetheless, a fair average for the stratigraphical frequency of the calcretes would be one profile for each 5 m of the succession upward from the base of the Temeside Shale Formation and its correlatives (Figure 1). Assigning a mean total thickness of 3 km to the Lower Old Red Sandstone, we arrive at a total of about 600 calcretes, or pedogenic events, in a vertical section such as a borehole core through the beds. Arguably the Lower Old Red Sandstone was accumulated over a period of about 20 Ma (Harland *et al.*, 1982), whence soil-forming conditions at a site could have occurred on the average roughly once every $3.33 \times 10^4$ years. The average duration of profile generation therefore cannot have exceeded this figure which, if it had actually been operative, would have left no time for the deposition of the host mudstones and sandstones. Of the mean total thickness of 3 km for the Lower Old Red Sandstone, about 1.54 km comprise non-calcretized floodplain mudstones. On the basis of our understanding of fluvial environments they are likely to have accumulated much more slowly than the partly laterally-deposited channel sandstones. If Leeder (1975) is correct in identifying a floodplain deposition rate of order $2 \times 10^{-3}$ m $a^{-1}$ as the limit to calcrete generation, the mudstqnes in the Lower Old Red Sandstone cannot in total represent more than about 1.15 Ma (consolidation by 33% to present thickness assumed). This result implies a maximum average duration of pedogenesis per calcrete profile of roughly $3.14 \times 10^4$ years, a figure not significantly different from the previous value based on total formation thickness. Thus the Lower Old Red Sandstone calcretes may not have horizonated at rates greater on the average than the order of $10^4$ years per profile, and it is possible that only a small fraction of the 20 Ma represented by the Lower Old Red Sandstone may, at any one site, have been spent in the normal accumulation of sediment.

## PALAEOGEOMORPHOLOGY

The formation of a soil requires the exposure of a parent material to the atmosphere over a sufficient period of time, so that the relevant physical and chemical processes and biological communities can become established, together with a state of geomorphic stability, so that soil horizons can be initiated and matured. In the context of an extensive region of alluviation, such as the Anglo-Welsh area during Old Red Sandstone times, the requirement of geomorphic stability at a site implies a pause in sedimentation, or at the very least a reduction in the sediment supply to a level at which soil-horizonation became possible. The abundance in the calcretes of features due to bioturbation is a clear and independent proof of the required reduction.

The required pauses must have been at least sub-regional in spatial extent, to judge from the evidence summarized above on the lateral range of individual calcretes. Such evidence, together with the truncated tops to many profiles, suggests a simple geomorphological model for the Anglo-Welsh area in Old Red Sandstone times (Allen and Williams, 1979). If one had been able to fly over the region at any time during the Pridoli, one might have seen extensive calcreted plains separating narrower but shallow valleys containing estuarine channels. Similarly, at any time during the Gedinnian and at least the bulk of the Siegenian, one might have witnessed similar plains divided by broad shallow valleys watered by rivers. The valleys in both cases reached back into the source-lands of the Old Red Sandstone, but the intervening plains bore their own smaller drainage systems, fed by local rain. To judge from the geomorphological expression of Quaternary calcretes (Goudie, 1973, 1983; Reeves, 1976), the Old Red Sandstone profiles in the later stages of their development could have formed caprocks underlying, and escarpments bordering, these level plains. The Abdon Limestone and its possible correlatives is a particularly mature and perhaps very extensive calcrete. Geomorphologically, it invites comparison with the plateau-forming calcretes of the Reynosa Cuesta, Edwards Plateau, and High Plains between the Kansas River and the Rio Grande in the south-western USA (Price, 1958; Swineford *et al.*, 1958; Goudie, 1973), and could record some especially significant event in the development of the Old Red Sandstone succession. There is certainly a noticeable change in fluvial facies across the Abdon Limestone in the Clee Hills (Allen, 1974b). The '*Psammosteus*' Limestones lower down in the succession undeniably record a substantial (0.25–0.5 Ma?) and regionally effective period of marked sediment starvation in the depositional basin. As there is a significant change of both depositional environment and sediment provenance vertically across this complex, it is possible that these calcretes owe

their existence to a geodynamic event which, by creating new uplifts, caused the eventual redirection of existing regional drainage and the establishment of new river systems (Allen 1974b).

## Palaeoclimate

Calcretes have been reported from some polar situations but, speaking generally, they are today most prevalent in and characteristic of a warm to hot climate (mean annual temperature 16–20°C) marked by a low but seasonal rainfall (100–500 mm) (Goudie, 1973, 1983). The Old Red Sandstone may therefore have formed under similar conditions, a conclusion consistent with the moderately low latitudinal position assigned on various independent grounds to the southern British Isles in the Devonian (e.g. Heckel and Witzke, 1979). The above suggestion can of course refer only to the depositional site, and must not be taken to imply that the Old Red Sandstone rivers were necessarily ephemeral or even flashy, as a significantly different climate could have prevailed in the source lands where their discharges orginated (e.g. Colorado River of California).

## Alluvial Architecture

One of the major current problems of fluvial sedimentology concerns the way in which the bodies of channel-related coarse sediment on the one hand and of overbank fines on the other fit together three-dimensionally to make up a fluvial formation. Another way of putting this is to ask how the essential palaeogeomorphology (Allen and Williams, 1979) sketched above may be projected through time to give us an assembly of sedimentary surfaces and enclosed deposits. The spatial scale on which this fit or assembly must be considered—kilometres to tens of kilometres horizontally and metres to tens of metres vertically—means that the question cannot generally be resolved from outcrop evidence but must be approached in other ways. Although this is not the place in which to review this now substantial field as a whole, it is worth noting that the pedogenic interpretation of the Old Red Sandstone calcretes is consistent to a degree with a number of models of fluvial architecture, depending on the factor(s) considered to be in control (Allen, 1974a).

Allen's first model envisaged pedogenesis as controlled by climatically-dependent proximal-distal shifts in the range of rivers entering the depositional basin. This model could be discounted for the Old Red Sandstone, primarily because it implied a pattern and occurrence of facies not recorded from the succession.

In three models an autocyclic cause is envisaged, pedogenesis being

controlled by lateral movements of the rivers, either continuously, in small steps, or in large avulsive steps. The last of these accords best with the behaviour of modern rivers and leads to quite realistic facies distributions.

A model in which the rivers shift only vertically in response to a purely allocyclic control (climatic change, base-level change, tectonism) is unacceptable, because channel sands, overbank muds and palaeosols could not then occur together in the one vertical profile. A combination of allocyclic and autocyclic factors, however, can create realistic sequences and the interfingering in three dimensions of channel with overbank sediment bodies. Remembering that the Anglo-Welsh area in late Silurian and Devonian times bordered a sea to the south, base-level change driving cyclic valley cutting and filling may have been the most significant factor controlling the geomorphology and sedimentology of the region. Evidence that base-level change may indeed have been a major allocyclic control comes from the Temeside Shale Formation and its correlatives, in which, on a scale of metres, sandstone complexes with a restricted marine fauna are interbedded vertically with mudstones (some also with lingulids) and calcretes (e.g. Dixon, 1921; Allen, 1974b; Allen and Williams, 1978). A lowering of base-level by no more than a few metres would have been all that was necessary to have brought a coastal mudflat into the vadose zone and the realm of pedogenesis.

## CONCLUSIONS

(1) As with fluvial formations in many parts of the stratigraphic record, calcretes are abundant and in many instances well-developed in the Old Red Sandstone facies (late Silurian–early Carboniferous) of the Anglo-Welsh area in the southern British Isles.
(2) The calcrete profiles vary widely in vertical extent, but are typically a few metres thick, revealing an upward increase in the size and density of calcite glaebules contained in a mudstone host and, in the case of the better developed ones, a massive to laminated uppermost part. Individual calcretes appear to have a lateral range measuring kilometres to tens of kilometres.
(3) Features due to bioturbation abound in the calcrete profiles and provide a clear and independent proof of an intermittent and drastic reduction in the local rate of sediment deposition.
(4) Systems of organized and slickensided fractures, some of which may be classified as pseudoanticlines and compared to *gilgai*, are common in the calcrete profiles and suggest superficial compressive effects related to seasonal clay swelling and drying and/or the displacive introduction of carbonate minerals.

(5) Many of the calcrete profiles are truncated upward by a surface of either weathering or erosion, overlain in the first instance by calcrete rubble and displaying in some cases solution phenomena, and in the second by an intraformational conglomerate or conglomerate complex.
(6) In terms of microscopic fabrics and textures, as well as field characteristics, the Old Red Sandstone calcretes compare closely with Quaternary calcretes and carbonate-bearing soils and may tentatively be referred largely to the Aridsol and Vertisol classes.
(7) The calcretes point to a warm, dry, seasonal climate in the Old Red Sandstone depositional basin, and to a basin landscape (known on other grounds to be fluvial) in which geomorphological change was drastic and frequent and, on the larger scale, under the control of allocyclic factors (mainly base-level oscillations?). The calcretes have a recurrence interval of about $3 \times 10^4$ years. In many cases a calcrete came to underlie a low plateau characterized by local drainage systems which fed laterally into one or more of the larger rivers crossing the alluvial plain from the distant source-lands of the Old Red Sandstone. Major geodynamic events affecting the accumulation of the Old Red Sandstone had a significant influence on calcrete pedogenesis within the depositional basin.

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